

# Inclusive and exclusive decays of doubly heavy baryons

**A.I.Onishchenko**

*Institute for Theoretical and Experimental Physics,  
B.Cheremushkinskaja, 25, Moscow, 117259 Russia  
Email: onischen@heron.itep.ru*

**ABSTRACT:** In this paper we give a short review of the recently obtained results on inclusive and exclusive decays of doubly heavy baryons.

**KEYWORDS:** OPE, QCD sum rules, NRQCD, weak decays, spin symmetry.

## 1. Introduction

Recently there was a big progress in our theoretical understanding of the physics of doubly heavy baryons. First, the production cross sections of doubly heavy baryons in hadron collisions at high energies of colliders and in fixed target experiments were calculated with the use of perturbative QCD for the hard processes and factorization hypothesis to account for the non-perturbative binding of heavy quarks inside the doubly heavy baryons [3]. Second, the lifetimes and branching fractions of some inclusive decay modes were evaluated in the Operator Product Expansion combined with the effective theory of heavy quarks [4, 5]. Third, the families of doubly heavy baryons, which contain a set of narrow excited levels in addition to the basic state, were described in the framework of potential models [6]. The picture of spectra, obtained in this analysis, is very similar to that of heavy quarkonia. Fourth, the QCD and NRQCD sum rules [7] were explored for the two-point baryonic correlators in order to calculate the masses and couplings of doubly heavy baryons [8, 9, 10]. And fifth, there are papers, where exclusive semileptonic and some nonleptonic decay modes of doubly heavy baryons in the framework of Bethe-Salpeter, NRQCD sum rules and potential models were analyzed [11, 12, 13]. In the present talk we will concentrate on the developments in the description of inclusive and exclusive decays of the mentioned hadrons. In what follows, we will present the results of OPE approach on lifetimes

and the results of three-point NRQCD sum rules on semileptonic and various nonleptonic decay modes of doubly heavy baryons.

## 2. Inclusive decays in OPE

In the first part of this review we give a short description of the OPE framework used to calculate lifetimes of doubly heavy baryons and present numerical predictions for their values. Here we also comment on relative contributions of spectator and nonspectator effects to estimated lifetimes.

### 2.1 OPE framework for lifetimes

Let us describe the calculation framework for the lifetimes of doubly heavy baryons on the concrete example of  $\Xi_{bc}^\diamond$  baryons. The optical theorem along with the hypothesis of integral quark-hadron duality, leads us to a relation between the total decay width of heavy quark and the imaginary part of its forward scattering amplitude. This relationship, applied to the  $\Xi_{bc}^\diamond$ -baryon<sup>1</sup> total decay width  $\Gamma_{\Xi_{bc}^\diamond}$ , can be written down as:

$$\Gamma_{\Xi_{bc}^\diamond} = \frac{1}{2M_{\Xi_{bc}^\diamond}} \langle \Xi_{bc}^\diamond | \mathcal{T} | \Xi_{bc}^\diamond \rangle, \quad (2.1)$$

with the transition operator  $\mathcal{T}$ :

$$\mathcal{T} = \mathcal{I}m \int d^4x \{ \hat{\mathcal{T}} H_{eff}(x) H_{eff}(0) \}, \quad (2.2)$$

where the effective lagrangian of weak interactions  $H_{eff}$ , for example, in the case of nonlep-

<sup>1</sup>Here  $\diamond$  denotes electrical charge of  $\Xi_{bc}^\diamond$ -baryon

tonic decays and at the characteristic hadron energies is given by

$$H_{eff} = \frac{G_F}{2\sqrt{2}} V_{q_3 q_4} V_{q_1 q_2}^* [C_+(\mu) O_+ + C_-(\mu) O_-] + h.c.$$

where

$$O_{\pm} = [\bar{q}_{1\alpha} \gamma_\nu (1 - \gamma_5) q_{2\beta}] [\bar{q}_{3\gamma} \gamma^\nu (1 - \gamma_5) q_{4\delta}] \times (\delta_{\alpha\beta} \delta_{\gamma\delta} \pm \delta_{\alpha\delta} \delta_{\gamma\beta}),$$

and

$$C_+ = \left[ \frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^{\frac{6}{33-2f}}, \quad C_- = \left[ \frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^{\frac{-12}{33-2f}},$$

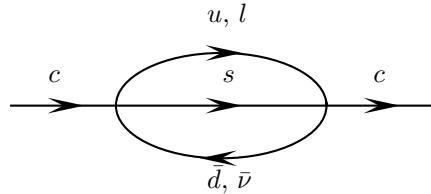
where  $f$  is the number of flavors and  $\{\alpha, \beta, \gamma, \delta\}$  run over the color indices.

As the energy release in heavy quarks decays is large, we may benefit from the Operator Product Expansion (OPE) for the transition operator

$$\begin{aligned} \mathcal{T} = \sum_{i=1}^2 & \{ C_1(\mu) \bar{Q}^i Q^i + \frac{1}{m_{Q^i}^2} C_2(\mu) \bar{Q}^i g \sigma_{\mu\nu} G^{\mu\nu} Q^i \\ & + \frac{1}{m_{Q^i}^3} O(1) \}. \end{aligned} \quad (2.3)$$

Performing the above expansion, we obtain a series of operators, classified according to their dimensions. The contributions of these operators to the total decay width of the baryon under consideration have a simple physical interpretation:

- dimension 3:  $\bar{Q}Q$ , this operator represents the contribution of spectator heavy quark decay.
- dimension 4: removed by the equations of motion.
- dimension 5:  $Q_{GQ} = \bar{Q}g\sigma_{\mu\nu}G^{\mu\nu}Q$ , represents chromomagnetic interaction of the decaying quark with other heavy quark as well as with the light quark.
- dimension 6:  $Q_{2Q2q} = \bar{Q}\Gamma q\bar{q}\Gamma' Q$ , the operators of this kind correspond to nonspectator effects, the most important of which are Pauli interference and weak scattering



**Figure 1:** The diagram of spectator contribution in the charmed quark decays.

Thus the transition operator can be written as

$$\begin{aligned} \mathcal{T}_{\Xi_{bc}^+} &= \mathcal{T}_{35b} + \mathcal{T}_{35c} + \mathcal{T}_{6,PI}^{(1)} + \mathcal{T}_{6,WS}^{(1)}, \\ \mathcal{T}_{\Xi_{bc}^0} &= \mathcal{T}_{35b} + \mathcal{T}_{35c} + \mathcal{T}_{6,PI}^{(2)} + \mathcal{T}_{6,WS}^{(2)}. \end{aligned}$$

All contributions in the above expressions can be explicitly calculated and, for example, the contribution of dimension 3 and 5 operators in the case of  $b$ -quark decay is given by the following expression

$$\mathcal{T}_{35b} = \Gamma_{b,spect} \bar{b}b - \frac{\Gamma_{0b}}{m_b^2} [2P_{c1} + P_{c\tau 1} + K_{ob}(P_{c1} + P_{cc1}) + K_{2b}(P_{c2} + P_{cc2})] O_{Gb},$$

where

$$\Gamma_{0b} = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2,$$

with  $K_{0Q} = C_-^2 + 2C_+^2$ ,  $K_{2Q} = 2(C_+^2 - C_-^2)$ ,

$$P_{c1} = (1-y)^4, \quad P_{c2} = (1-y)^3, \quad y = \frac{m_c^2}{m_b^2}.$$

Below, we have also written a characteristic non-spectator contribution given by electroweak scattering of  $b$  and  $c$ -quarks

$$\begin{aligned} \mathcal{T}_{WS,bc} = & \frac{G_F^2 |V_{cb}|^2}{4\pi} m_b^2 (1 + \frac{m_c}{m_b})^2 (1 - z_+)^2 \times \\ & [(C_+^2 + C_-^2 + \frac{1}{3}(1 - k^{1/2})(C_+^2 - C_-^2)) \times \\ & (\bar{b}_i \gamma_\alpha (1 - \gamma_5) b_i)(\bar{c}_j \gamma^\alpha (1 - \gamma_5) c_j) + \\ & k^{1/2} (C_+^2 - C_-^2) \times \\ & (\bar{b}_i \gamma_\alpha (1 - \gamma_5) b_j)(\bar{c}_j \gamma^\alpha (1 - \gamma_5) c_i)], \end{aligned}$$

where

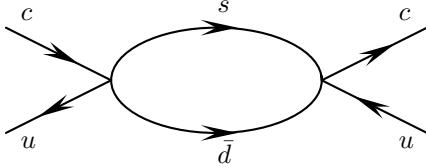
$$z_+ = \frac{m_c^2}{(m_b + m_c)^2}, \quad k = \frac{\alpha_s(\mu)}{\alpha_s(m_b + m_c)}.$$

The hadronic matrix elements can be further estimated using effective theories description of bound

	$\Xi_{cc}^{++}$	$\Xi_{cc}^+$	$\Omega_{cc}^+$
$\sum c \rightarrow s, \text{ ps}^{-1}$	3.104	3.104	3.104
PI, $\text{ps}^{-1}$	-0.874	-	0.621
WS, $\text{ps}^{-1}$	-	1.776	-
$\tau, \text{ ps}$	0.45	0.20	0.27

**Table 1:** The lifetimes of doubly charmed baryons together with the relative spectator and nonspectator contributions to the total widths.

state dynamics of doubly heavy baryons. Here we will not give the details of these estimates and refer the interested reader for details to [4, 5]. So, in the next subsection, we will go directly to the numerical estimates of doubly heavy baryon lifetimes.



**Figure 2:** The diagram for the contribution of Pauli interference in the decays of charmed quark for the  $\Xi_{bc}^+$  baryon.

## 2.2 Numerical results

Now we have already estimates for the lifetimes of all doubly heavy baryons [4, 5]. However, there is some difference in concrete numerical values of lifetimes obtained in different papers. In papers [5] we have commented on the uncertainties in the resulting values of lifetimes related to the values of heavy quark masses. Besides this, there is one more uncertainty remained due to the value of light quark - diquark wave-function at origin. Today there are two approaches to estimate this value: 1) assuming, that this value is the same as the value of  $D$  - meson wave function at origin; 2) extracting this value from the comparison of hyper-fine splittings in doubly heavy and singly heavy baryons. Here we give the results of the lifetime estimates made in the second approach, as they are the most complete.

From Tables 1.-3. we see a sizeable contribution of nonspectator effects to the lifetimes of doubly heavy baryons. The presence of the lat-

	$\Xi_{bc}^+$	$\Xi_{bc}^0$	$\Omega_{bc}^0$
$\sum b \rightarrow c, \text{ ps}^{-1}$	0.632	0.632	0.631
$\sum c \rightarrow s, \text{ ps}^{-1}$	1.511	1.511	1.509
PI, $\text{ps}^{-1}$	0.807	0.855	0.979
WS, $\text{ps}^{-1}$	0.653	0.795	1.713
$\tau, \text{ ps}$	0.28	0.26	0.21

**Table 2:** The lifetimes of  $(bcq)$ -baryons together with the relative spectator and nonspectator contributions to the total widths.

	$\Xi_{bb}^0$	$\Xi_{bb}^-$	$\Omega_{bb}^-$
$\sum b \rightarrow c, \text{ ps}^{-1}$	1.254	1.254	1.254
PI, $\text{ps}^{-1}$	-	-0.0130	-0.0100
WS, $\text{ps}^{-1}$	0.0189	-	-
$\tau, \text{ ps}$	0.79	0.80	0.80

**Table 3:** The lifetimes of  $(bbq)$ -baryons together with the relative spectator and nonspectator contributions to the total widths.

ter, for example, leads to a huge difference of  $(ccq)$ -baryon lifetimes.

## 3. Exclusive decays in NRQCD sum rules

In this section we review the results for exclusive decay modes of doubly heavy baryons, obtained in the framework of three-point NRQCD sum rules. Our consideration of form-factors, governing the above transitions, will be restricted to the case of spin 1/2 - spin 1/2 baryon transitions. We will comment on the size of spin 1/2 - spin 3/2 contribution in the section with our numerical results.

### 3.1 Two point sum rules

We start with the two-point NRQCD sum rules for corresponding baryonic couplings. For baryons, containing two heavy quarks, there are two distinct choices of baryonic interpolating currents: 1) The prescription with the explicit spinor structure of the heavy diquark from the very beginning

$$\begin{aligned} J_{\Xi_{QQ'}^{\circ}} &= [Q^{iT} C \tau \gamma_5 Q^{j'}] q^k \varepsilon_{ijk}, \\ J_{\Xi_{QQ}^{\circ}} &= [Q^{iT} C \tau \gamma^m Q^j] \cdot \gamma_m \gamma_5 q^k \varepsilon_{ijk}, \end{aligned} \quad (3.1)$$

2) The currents, which require further symmetrization of heavy diquark wave function

$$J_{\Xi_Q^0} = \varepsilon^{\alpha\beta\gamma} : (Q_\alpha^T C \gamma_5 q_\beta) Q_\gamma' : \quad (3.2)$$

In calculations of exclusive decay modes from three-point NRQCD sum rules, considered below, we will use the currents of the second type. For the benefits of this choice we refer the reader to [13]. The baryon couplings for both types of currents are defined as usual

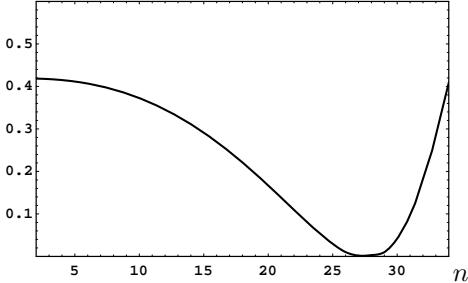
$$\langle 0 | J_H | H(p) \rangle = i Z_H u(v, M_H) e^{ip \cdot x} \quad (3.3)$$

To estimate the introduced baryonic couplings, we consider two-point correlation function of corresponding currents

$$\Pi^{(2)} = i \int d^4x e^{ipx} \langle 0 | T\{J(x), \bar{J}(0)\} | 0 \rangle = \not{p} F_1(p^2) + F_2(p^2), \quad (3.4)$$

where  $v$  is the four-velocity of the studied doubly heavy baryon.

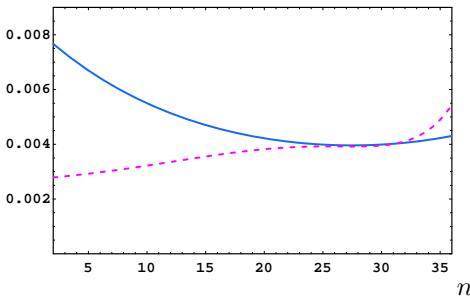
$\Delta M_{\Xi_{bc}}$ , GeV



**Figure 3:** The difference between the  $\Xi_{bc}$ -baryon masses calculated in the NRQCD sum rules for the formfactors  $F_1$  and  $F_2$  in the scheme of moments for the spectral densities (first type of currents).

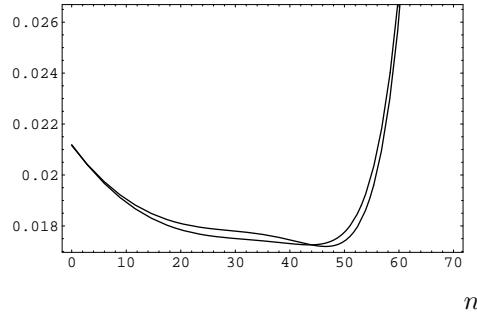
For both types of currents the NRQCD sum rules derived include coulomb-like corrections in the system of doubly heavy diquark as well as contributions of nonperturbative terms coming from the quark, gluon, mixed condensates and the product of quark and gluon condensates[9, 13]. As was shown by the authors of [8], for the second type of currents it is difficult, in general, to achieve a stability of sum rules predictions for the both extracted mass and coupling of doubly

$|Z_{\Xi_{bc}}|^2$ , GeV<sup>2</sup>



**Figure 4:** The couplings  $|Z_{\Xi_{bc}}^{(1,2)}|^2$  of  $\Xi_{bc}$ -baryon calculated in the NRQCD sum rules for the formfactors  $F_1$  and  $F_2$  in the scheme of moments for the spectral densities (first type of currents).

$|Z_{\Xi_{bb}}|^2$ , GeV<sup>2</sup>



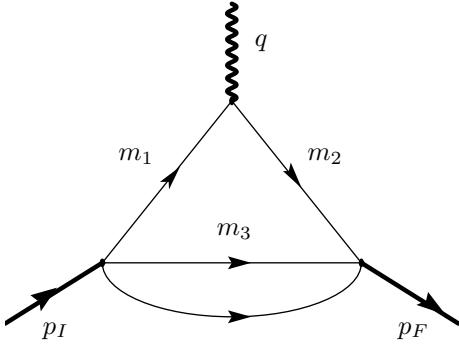
**Figure 5:** The couplings  $|Z_{\Xi_{bb}}^{(1,2)}|^2$  of  $\Xi_{bb}$ -baryon calculated in the NRQCD sum rules for the formfactors  $F_1$  and  $F_2$  in the scheme of moments for the spectral densities (second type of currents).

heavy baryons. So, for the second type of currents used here, we evaluate the coupling constants only and use the masses of doubly heavy baryons, calculated by us previously [9], as inputs.

The results of the performed analysis can be most conveniently understood from the figures below. The plotted result for the  $\Xi_{bb}$ -baryon coupling of the second type does not include the Coulomb corrections, as the calculation of desired form-factors for the doubly heavy baryons can be consistently performed without accounting for Coulomb corrections either, provided we neglect them both in the two-point and three-point sum rules<sup>2</sup>.

<sup>2</sup>For more details see [13, 16]

### 3.2 Three-point sum rules



**Figure 6:** The diagram, corresponding to the three-point correlation function considered in the paper.

Following the standard procedure for the evaluation of form-factors in the framework of NRQCD sum rules, we consider the three-point correlation function

$$\Pi_\mu = i^2 \int d^4x d^4y \langle 0 | T\{ J_{H_F}(x) J_\mu(0) \bar{J}_{H_I} \} | 0 \rangle \times e^{ip_F \cdot x} e^{-ip_I \cdot y} \quad (3.5)$$

The theoretical expression for the three-point correlation function can be easily calculated with the use of double dispersion relation

$$\begin{aligned} \Pi_\mu^{(theor)}(s_1, s_2, q^2) = & \\ \frac{1}{(2\pi)^2} \int_{m_I^2}^\infty ds_1 \int_{m_F^2}^\infty ds_2 \frac{\rho_\mu(s_1, s_2, q^2)}{(s_1 - s_1^0)(s_2 - s_2^0)} + \dots & \end{aligned} \quad (3.6)$$

Saturating the channels of initial and final state hadrons by ground states of corresponding baryons, we have the following phenomenological expression for the three-point correlation function

$$\begin{aligned} \Pi_\mu^{(phen)}(s_1, s_2, q^2) = & \sum_{spins} \frac{\langle 0 | J_{H_F} | H_F(p_F) \rangle}{s_2^0 - M_{H_F}^2} \times \\ & \langle H_F(p_F) | J_\mu | H_I(p_I) \rangle \times \\ & \frac{\langle H_I(p_I) | \bar{J}_{H_I} | 0 \rangle}{s_1^0 - M_{H_I}^2} \end{aligned} \quad (3.7)$$

The formfactors for spin  $\frac{1}{2}$  – spin  $\frac{1}{2}$  baryon transitions are modeled as following

$$\begin{aligned} \langle H_F(p_F) | J_\mu | H_I(p_I) \rangle = & \bar{u}(p_F) \{ \gamma_\mu G_1^V + v_\mu^I G_2^V + \\ & v_\mu^F G_3^V + \gamma_5 (\gamma_\mu G_1^A + \\ & v_\mu^I G_2^A + v_\mu^F G_3^A) \} u(p_I) \end{aligned}$$

Naively, all these six formfactors are independent. However, the analysis of spin symmetry relations in the limit of zero recoil shows the semileptonic decays of doubly heavy baryons can be described by the only universal function, an analogue of Isgur-Wise function[13, 11].

So, now we in position, where to obtain estimates on semileptonic or nonleptonic transitions under hypothesis of factorization [17] we should calculate the only universal function.

The calculation of spectral densities is straightforward with the use of Cutkosky rules for quark propagators [15]. The results for the trace of correlation function with  $v_\mu^I$  are

- 1) heavy to heavy underlying quark transition

$$\rho^{pert} = \int_{m_3^2}^{(\sqrt{s_1} - m_1)^2} \frac{6}{(2\pi)^4} \frac{m_1 m_2 (k^2 - m_3^2)^2}{k^2 (\lambda(s_1, s_2, q^2))^{1/2}} dk^2 \quad (3.8)$$

$$\rho^{\bar{q}q} = -\frac{4}{(2\pi)^2} \frac{m_1 m_2 m_3 \sqrt{s_1}}{(m_1 + m_3) (\lambda(s_1, s_2, q^2))^{1/2}} \langle \bar{q}q \rangle \quad (3.9)$$

$$\begin{aligned} \cos \theta = & \frac{m_2}{|\vec{p}_2| |\vec{k}|} (\sqrt{s_1} - p_{20} + (m_2 - m_1) \times \\ & (1 - \frac{|\vec{k}|^2}{2m_1 m_2}) + \frac{|\vec{p}_2|^2}{2m_2}) \end{aligned} \quad (3.10)$$

- 2) heavy to light underlying quark transition

$$\rho^{pert} = \int_{m_3^2}^{(\sqrt{s_1} - m_1)^2} \frac{3F_1}{4(2\pi)^4} \frac{(k^2 - m_3^2)^2}{k^2 (\lambda(s_1, s_2, q^2))^{1/2}} dk^2 \quad (3.11)$$

$$\rho^{\bar{q}q} = -\frac{m_1 m_3 \sqrt{s_1} F_2}{2(m_1 + m_3) (\lambda(s_1, s_2, q^2))^{1/2}} \langle \bar{q}q \rangle \quad (3.12)$$

$$\begin{aligned} \cos \theta = & \frac{1}{2|\vec{p}_2| |\vec{k}|} (2p_{20}(\sqrt{s_1} - m_1 - \frac{|\vec{k}|^2}{2m_1}) - s_2 \\ & - (\sqrt{s_1} - m_1)^2 + \frac{\sqrt{s_1} |\vec{k}|^2}{m_1} + m_2^2) \end{aligned} \quad (3.13)$$

where

$$F_1 = \frac{2}{\sqrt{s_1}} (m_1^2 - q^2 + 2m_2 \sqrt{s_1} + s_2 - k^2) \quad (3.14)$$

$$F_2 = F_1|_{k^2 \rightarrow m_3^2} \quad (3.15)$$

The notations in the above expressions should be clear from Fig. 6. Having derived theoretical

expressions for the three-point correlation function, we may proceed now with the evaluation of form-factors. In numerical estimates we will use the Borel scheme for the form-factor extraction and so, below we give the formula determining the universal Isgur-Wise function for the semileptonic decays of doubly heavy baryons

$$\xi^{IW}(q^2) = \frac{1}{(2\pi)^2} \frac{1}{8M_I M_F Z_I Z_F} \int_{(m_1+m_3)^2}^{s_I^{th}} \int_{(m_1+m_2)^2}^{s_F^{th}} \rho(s_I, s_F, q^2) ds_I ds_F \times \exp\left(-\frac{s_I - M_I^2}{B_I^2}\right) \exp\left(-\frac{s_F - M_F^2}{B_F^2}\right), \quad (3.16)$$

where  $B_I$  and  $B_F$  are the Borel parameters in the initial and final state channels.

### 3.3 Numerical estimates

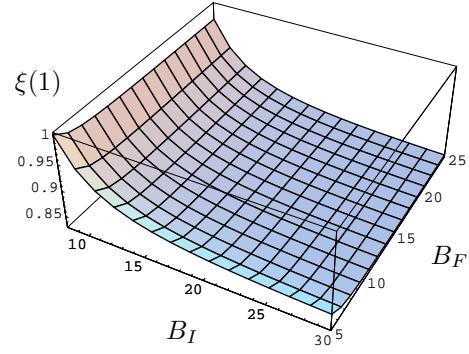
The analysis of NRQCD sum rules in the Borel scheme gives us the estimates of the value of Isgur-Wise (IW) function at zero recoil for different types of spin 1/2 - spin 1/2 transitions between doubly heavy baryons, shown in Table 4. For the sake of comparison, we also provide here the estimates of the values of IW-function at zero recoil performed by us in the framework of potential models, which can be also found in Table 4. We see that within the errors of the sum rule method (15%) the obtained results are very close to each other.

Mode	$\xi(1)$ SR	$\xi(1)$ PM
$\Xi_{bb} \rightarrow \Xi_{bc}$	0.85	0.91
$\Xi_{bc} \rightarrow \Xi_{cc}$	0.91	0.99
$\Xi_{bc} \rightarrow \Xi_{bs}$	0.9	0.99
$\Xi_{cc} \rightarrow \Xi_{cs}$	0.99	1.

**Table 4:** The normalization of Isgur-Wise function for different baryon transitions at zero recoil.

In Fig.7 we have plotted the dependence of the normalization of IW-function on the Borel parameters of initial and final state baryons in the case of  $\Xi_{bb} \rightarrow \Xi_{bc}$  transition.

Next, to obtain the dependence of formfactors on the square of momentum transfer we ex-



**Figure 7:** The value of  $\xi(1)$  for the transition  $\Xi_{bb}^\diamond \rightarrow \Xi_{bc}^\diamond$  as function of Borel parameters in the  $s_I$  and  $s_F$  channels.

ploit the pole resonance model. So, for the IW-function we have the following expression:

$$\xi^{IW}(q^2) = \xi_0 \frac{1}{1 - \frac{q^2}{m_{pole}^2}}, \quad (3.17)$$

with

$$m_{pole} = 6.3 \text{ GeV for the } b \rightarrow c \text{ transitions}$$

$$m_{pole} = 1.85 \text{ GeV for the } c \rightarrow s \text{ transitions.}$$

With the obtained estimates for the formfactors, we can easily obtain the predictions for the semileptonic and some nonleptonic decay modes of doubly heavy baryons. The results of such estimates can be found in Table 2.

Mode	Br (%)	Mode	Br (%)
$\Xi_{bb}^\diamond \rightarrow \Xi_{bc}^\diamond l \bar{\nu}_l$	14.9	$\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} l \bar{\nu}_l$	4.9
$\Xi_{bc}^0 \rightarrow \Xi_{cc}^+ l \bar{\nu}_l$	4.6	$\Xi_{bc}^+ \rightarrow \Xi_{bs}^0 l \nu_l$	4.4
$\Xi_{bc}^0 \rightarrow \Xi_{bs}^- l \nu_l$	4.1	$\Xi_{cc}^{++} \rightarrow \Xi_{cs}^+ l \nu_l$	16.8
$\Xi_{cc}^+ \rightarrow \Xi_{cs}^0 l \nu_l$	7.5	$\Xi_{bb}^\diamond \rightarrow \Xi_{bc}^\diamond \pi^-$	2.2
$\Xi_{bb}^\diamond \rightarrow \Xi_{bc}^\diamond \rho^-$	5.7	$\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} \pi^-$	0.7
$\Xi_{bc}^0 \rightarrow \Xi_{cc}^+ \pi^-$	0.7	$\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} \rho^-$	1.9
$\Xi_{bc}^0 \rightarrow \Xi_{cc}^+ \rho^-$	1.7	$\Xi_{bc}^+ \rightarrow \Xi_{bs}^0 \pi^+$	7.7
$\Xi_{bc}^0 \rightarrow \Xi_{bs}^- \pi^+$	7.1	$\Xi_{bc}^+ \rightarrow \Xi_{bs}^0 \rho^+$	21.7
$\Xi_{bc}^0 \rightarrow \Xi_{bs}^- \rho^+$	20.1	$\Xi_{cc}^{++} \rightarrow \Xi_{cs}^+ \pi^+$	15.7
$\Xi_{cc}^+ \rightarrow \Xi_{cs}^0 \pi^+$	11.2	$\Xi_{cc}^{++} \rightarrow \Xi_{cs}^+ \rho^+$	46.8
$\Xi_{cc}^+ \rightarrow \Xi_{cs}^0 \rho^+$	33.6		

**Table 5:** Branching ratios for the different decay modes of doubly heavy baryons.

To calculate the branching ratios for exclusive decay modes we used the values of doubly heavy baryon lifetimes, calculated by us previously [5]. The values, presented in Table 2 already include the contribution of spin 1/2-spin 3/2 decay channels. To estimate the latter we have used the results of [11], where the contribution of these channels was calculated for the case of  $\Xi_{bc} \rightarrow \Xi_{cc} + l\bar{\nu}$  baryon transition, and assumed, that, according to superflavor symmetry, it constitutes 30 % from the contribution of corresponding spin 1/2-spin 1/2 transitions for all transitions between doubly heavy baryons. In calculations of  $\Xi_{bb}^\diamond$  and  $\Xi_{cc}^\diamond$ -baryon decay modes we have taken into account a factor 2 due to Pauli principle for the identical heavy quarks in the initial channel. In the case of  $\Xi_{bc}^\diamond \rightarrow \Xi_{cc}' X$ -baryon transition the same factor comes from the positive Pauli interference of the  $c$ -quark, being a product of  $b$ -quark decay, with the  $c$ -quark from the initial baryon. Here, we also would like to mention, that for the  $\Xi_{bc}$ -baryon decays the mentioned positive Pauli interference contribution is dominant compared to other nonspectator contributions<sup>3</sup>, so we do not introduce other corrections here. However, in the case of  $\Xi_{cc}^{++} \rightarrow \Xi_{cs}^+ X$ -baryon transition the negative Pauli interference plays the dominant role and thus should be accounted for explicitly. From the previously done OPE analysis for doubly heavy baryon lifetimes [4, 5] we conclude that the corresponding correction factor in this case is 0.62. We would like also give a small comment on our notations. The  $\Xi_Q^\diamond$ s in Table 2 stays for the sum of  $\Xi_Q^\diamond$  and  $\Xi_Q^{\diamond'}$  decay channels. The obtained results are in agreement with the previous estimates of  $\Xi_{bc}$ -baryon exclusive decay modes [11] and with the results of OPE analysis [4, 5] for inclusive decay modes.

#### 4. Conclusion

In this paper we have made a short review on the inclusive and exclusive decay modes of doubly heavy baryons. The results on the lifetimes of doubly heavy baryons as well as estimates of semileptonic, pion and  $\rho$ -meson decay modes are given.

<sup>3</sup>Here we use the results of OPE analysis for the inclusive decay modes of doubly heavy baryons [4, 5]

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